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Multi-axis 3D printing of material reduced shell structures on a reconfigurable supporting system using topology optimization principles

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Abstract

The last few decades, the application of 3D Printing (3DP) techniques in construction scale has shown an increased trend, with advantages as well as limitations, mainly related to overhanging angle restrictions during printing of complex geometries including free-form shell structures. This work suggests a five steps methodology as an alternative approach for their design and then their 3DP. In particular, in the first stage, parametric design based on the catenary concept is used for the overall geometrical configuration of free-form shells, aiming at minimization of exercised tension and compression forces. Then, Topology Optimization (TO) principles are applied, in order to reduce total material volume and at the same time to achieve structural stability of the selected shell system. This is followed by an approach for alternating individual unit members based on the functionally graded cellular structures concept, which aims at material distribution and customization in different areas. In the fourth stage, a reconfigurable formwork system is developed and used as a supporting structure for on-site 3DP in different angles and for different design configurations. Finally, the 3DP process of toolpath development and simulation are demonstrated, accompanied by real scale physical experimentation. The work is assessed in providing initial information regarding the effectiveness of the process to be used in the construction of shell structures through multi-axis 3DP assisted by reconfigurable supporting systems.

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Keywords: Multi-axis 3D printing; Topology Optimization; reconfigurable supoorting system; shell structures.

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1. Introduction

The design and physical production steps in shell structures' development are important directions of structural investigations in the 21st century. Within this framework, several shell construction strategies can be found, including among others cable-net systems, cable-net systems with nodes, fabric formwork systems and grid structures net systems [1].

Considering the research and practical applications in this area so far, it is widely recognized that the design optimization and construction of shells contain many challenges that require continuous and in-depth investigation. Nowadays, two widely accepted research directions that could contribute to the design optimization and the efficient construction of such structures are Topology Optimization (TO) and 3D Printing (3DP) respectively. These two directions can be integrated by combining techniques that include, among others, computational design and digital fabrication [2]. The first aspect of such an approach, that of TO, describes a mathematical method that optimizes material distribution by using parameters such as design space, set of loads, boundary conditions and constraints with the goal to minimize the material used and to maximize the structural performance of the system. Results derived from TO can been further refined by implementing size and/or shape optimization approaches in order to improve the design under investigation [3].

The second aspect, that of Additive Manufacturing (AM), and more specifically 3D Printing (3DP) techniques in construction scale, e.g. Contour Crafting (CC) [4], has shown an increased trend in the last few decades with advantages in maximization of construction speed as well as minimization of material waste and construction cost. A number of constraints are also observed, mainly in relation to the printing of complex geometries due to the limitation of existing techniques, which are mostly applied in 2.5-dimensional shapes and with overhanging restrictions at specific angles. Several 3DP techniques can be found in architectural scale examples using different materials like polymers, ceramics and cementitious ones, with the latter to be the most widely used approach, representing a great challenge in the construction industry [5]. In case of concrete 3DP, crane systems are mostly applied, which can print in XYZ directions, offering at the same time a fast, accurate and economic solution in construction. Moreover, robotic 3DP methods are observed, which can print in XYZ directions in a more portable manner, but with limitations regarding the printing area, leading to physical prototypes, mostly produced off-site in comparison with crane systems that are used for on-site 3DP and particularly for printing execution of entire structures. Further printing methods include, among others, D-Shape [6] and BatiPrint [7]. D-Shape is a binder jetting 3D Printing technology, where a liquid binder is applying on each individual layer of powder material for the production of a strong cement-based material. BatiPrint is a technique where a mold is 3D printed by spraying polyurethane layer by layer as supporting structure and then concrete is poured inside. The outer 3D printed structure remains and is used as insulation, therefore the structure is created in a kind of reversed manner compared to the traditionally process of wall construction.

Despite the increased application of 3DP techniques for building construction, only few of them have been involved in the construction of free-form shapes including shell structures. Examples like the European Space Agency project [8] suggested a 3DP technique for shell building development on the moon using local regolith material. In this case, the D-shape method was applied using local materials, because of the specificity of the printing area and the gradient, resulting in economical and faster completion of the construction tasks [8]. Also, at laboratory level, examples can be found where concrete 3DP is applied on curved surfaces, that are used as supporting systems until printing parts are hardened and assembled together, comprising the overall concrete shell structure [9]. The examples so far show that a number of obstacles need to be overcome, including restrictions related to the range of free-form shapes that can be developed and limitations regarding the overhang angles that can be printed [10].

This research takes into account existing limitations and constraints on 3DP of shell structures at construction scale and suggests a methodology that integrates parametric design that includes structural analysis based on TO principles and a multi-axis robotic 3DP technique using a reconfigurable structure as the supporting system in order to overcome overhang limitations. The aim is twofold, on one hand the structural optimization attempts to reduce material and achieve optimum mass distribution while maintaining the static behavior of structure, and on the other hand, 3DP methodology intents to achieve printing in different surface inclinations that can be found in any free-form shell structure.

2. Methodology & Process development

The suggested integrated methodology that combines TO principles and 3DP is divided into five stages, which consist of different sub-stages. In the first stage, the parametric design of shell structures is conducted. In this stage, the overall definition and control of shell design is defined by two curves, where multiple catenary chains are applied for form-finding (curves are constrained according to the angles of 4-point and 3-axis slopes). Then, the initial results are topologically analyzed, aiming at reducing the required material for printing, decreasing at the same time the construction time and cost. The third stage includes a process based on the concept of functionally graded cellular structures [11]. According to this approach, the shell structure is reshaped into a triangular grid-like structure consisting of triangular cells. The purpose is to accommodate the 3D printing process, incorporating at the same time the material reduction based on TO results [2]. Then, a reconfigurable formwork system is developed as supporting system for 3DP. The formwork can be easily assembled and disassembled on-site according to the shell shape under construction. Finally, due to the large scale of the printing and the need for multi-axis movement while switching between the triangular pattern, a robotic machine mounted on a crane is used. This allows flexibility in 3D printing of shapes in various directions, following the curvature of geometry under investigation [Fig 1].

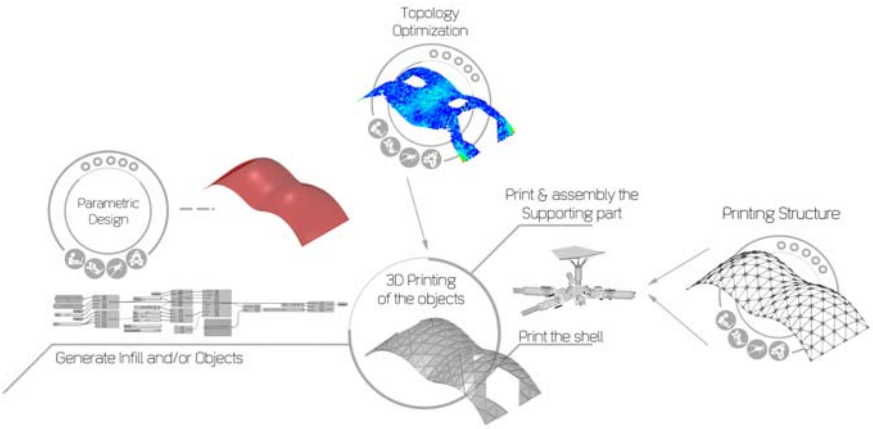


Fig. 1 Diagrammatic representation of the five stages of methodology including TO and 3DP process development.

3. Parametric design & Optimization

3.1. Parametric 3D Modelling

The parametric design of shell structure aims at achieving flexibility in selecting and modifying different shell shapes, using either two or four base curves with the addition of multiple catenary curves, in order to reduce tensile forces and to produce self-contained surfaces. The final shell could be either autonomously incorporated into the space as a pavilion or as an addition of an already existing construction. The shell design is divided into five steps (by importing two or four different curves in the algorithm) in an associative sequence within the parametric environment and includes: the division of the curve in an odd number, the generation of a catenary chain using gravity and the self-weight of the structure, the generated offset catenary chain to the inner part of the structure (thickness), the creation of the two surfaces (inner & outer) using the catenary chain and the development of the shell structure with double curvature.

3.2. Structural Analysis & Topology Optimization

The integration of TO, static analysis and 3DP aims at decreasing the total weight of the structure by removing material from the areas of shell geometry with minimum stress [2], allowing less printing time and material usage but also less energy consumption. The plug-in Ameba [12] for Grasshopper [13] parametric environment is used for TO. Ameba provides result based on the parametrically developed shell structures, which include, among others, Von Mises and principal stresses value list with, or without optimization of the geometry. In this investigation, values derived from Ameba plug-in are confirmed by the structural analysis program Scan & Solve [Fig.2].

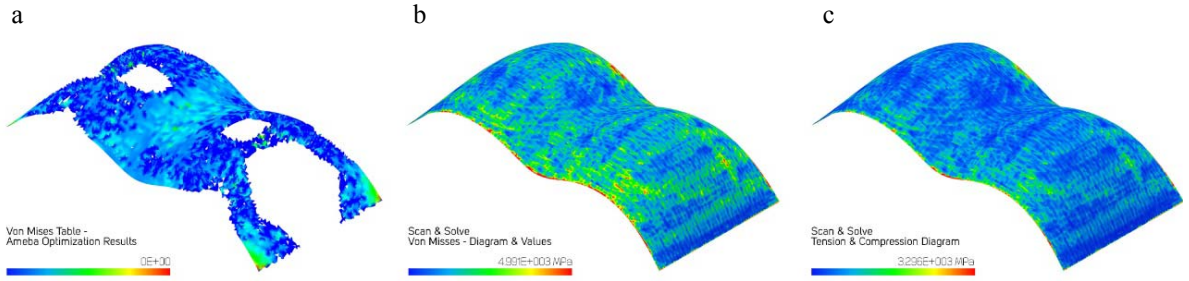


Fig. 2 Results extracted from Ameba and Scan & Solve plug-ins. a. Von Mises results together with the areas that minimum material is required based on Ameba plug-in, b. Von Mises diagram based on Scan & Solve plug-in, c. Tension and compression diagram based on Scan & Solve plug-in.

3.3. Functional graded material distribution

In this stage, the shell structure is divided into triangular cells using the LunchBox plug-in [14]. The purpose of the grid development is to create a net system, which can be used, both for a continuous triangular 3D printing path but also for formulating a formwork system in a later stage that can accommodate the 3DP process, supporting the whole printed body. Within this framework, initially the distribution of material in each triangular cell is achieved by following the results of TO and by applying the functionally graded material distribution approach. According to this, the areas with zero stresses are excluded from the printing process. Then, the Von Mises results are grouped by values and are geometrically associated with the corresponding triangles on the grid surface, followed by their internal separation in layers (1 offset triangle (values: -99.999), 2 offset triangles (values: 100.000-199.999), 3 offset triangles (values: 200.000-299.999) and 4 offset triangles (values: 300.000+)) [Fig. 3 & 4].

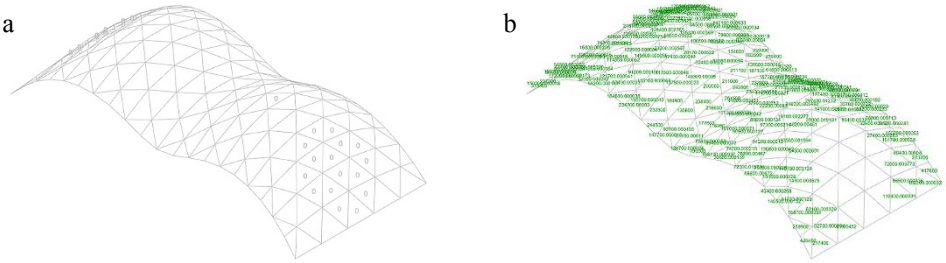


Fig. 3 Results extracted from Ameba and Scan & Solve plug-ins. a. The areas with zero stress, b. The values of each triangle.

In detail, at Layer 1 all the triangular surfaces are printed. Then, each layer of triangles is offset inwards until the overall shape for 3D printing is defined. In the final Layer 8, a transparent surface is used to cover the shell, preventing the interior from rain or other unpleasant weather conditions.

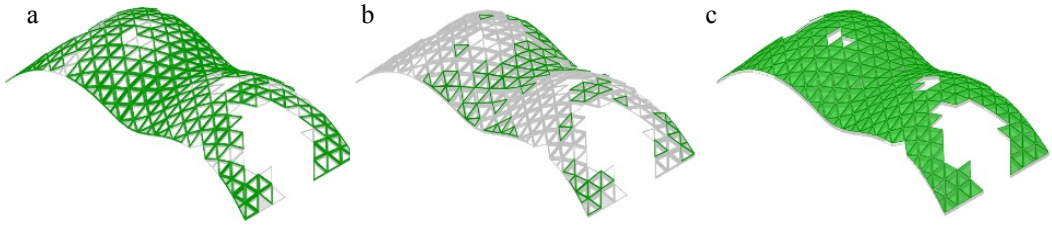


Fig. 4. Printing layers according to functionally graded material distribution (a. Layer 1, b. Layer 5 and 6, c. Layer 8)

4. Reconfigurable Formwork system

In this stage, a reconfigurable formwork system is developed to support the structure while 3DP execution takes place, allowing at the same time flexibility in its use but also effectiveness during on-site assembly and disassembly in various geometries. In addition, the reconfigurable system facilitates the continuous 3DP on the curved surface, without any required external changes. In detail, the formwork contains multiple semi-circular nodes. Each individual semi-circular node can fit up to six 180^{o} Net Pile Beams and one Supporting Column System. The minimum distance between two Net pile beams is 45cm and the maximum is around 1m [Fig. 5].

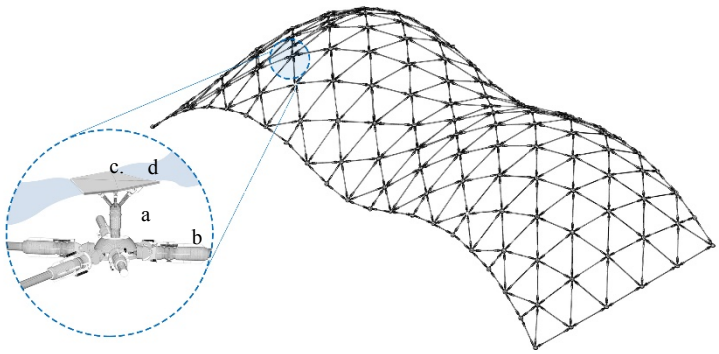
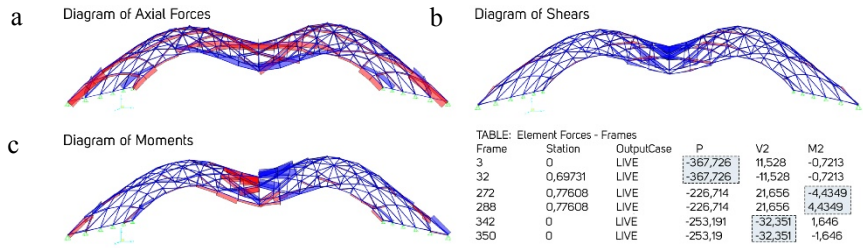


Fig. 5 The reconfigurable formwork system with node detail (a. Semi-circular node, b. 180^{o} Net pile beam, c. Supporting column, d. Membrane)

As part of the reconfigurable formwork system investigation, structural analysis using SAP2000 is conducted in order to achieve minimization of failures that might occur during the 3D printing stage, but also to verify the size of structural members. Particularly, analysis of loads, axial and shear forces, torques and distortions are conducted and evaluated in order to define the final design of the reconfigurable formwork system [Fig. 6].



Fi. 6 Results derived from SAP2000 analysis of formwork system. a) Axial Forces, b) Shear Forces, c) Moments

5. 3D Printing

5.1. 3D Printing pre-processing

For the robotic tool-path planning, the Taco ABB plug-in [15] for Grasshopper is used and is integrated with an in-house algorithm that achieves 3DP control in a seamless process from design to robotic 3DP [16]. The system of triangle cells that formulate the overall structure is converted to points and planes, followed by their connection in a continuous toolpath. In addition, the robotic movement in each triangle changes its printing plane by associating information related to inclinations, directions and angles of triangles over the whole shell geometry. Figure 7a shows changes of the angles of the 3DP extruder during printing in different surface triangles until the entire system of triangles is printed. The 3D printing method is based on Contour Crafting with layers deposited in cross sectional arrangement in order to maximize the static behaviour of the printing results [Fig. 7b].

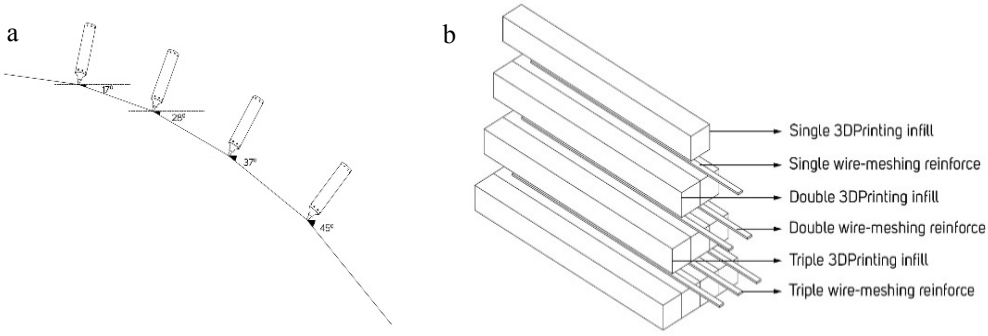


Fig. 7 a. Different angles of 3DP extruder during the printing process, b. Contour crafting of the layers in one triangle unit

5.2. 3D Printing of an experimental case study

The 3DP process aims at evaluating the approach and extracting information related to associated issues like the selection of the appropriate material mixtures, the printing speed and the durability of the entire shell construction. Within this framework, the load behavior, the maximum angle of printing planes and the strength of materials together with the size of triangle surface that are printed have direct impact and influence the overall 3DP process. Hence, in this stage, an experimental case study is conducted, in order to extract useful information for further investigation. The first step is the toolpath generation using Taco ABB plug-in based on the 3DP programming

undertaken in the previous part of the process, aiming at geometrical adjustments in order to achieve static adequacy of the system using less quantity of material.

Analytically, six triangular elements are tested by simulating their 3DP process and then information is transferred to the robotic machine for 3D printing execution. The elements are filled with infill material based on the thickness of nozzle that can influence the number of repeats, in order to achieve printing of a single geometry (range between 1 to 4 repeats). At the same time, thickness and height of material filament remain constant throughout printing (1.5cm). In this case study, a total of 32 layers of printing is conducted [Fig. 8a]. The 3DP extruder is based on a piston mechanism [Fig. 8c] and is used to control the speed and pressure of the material being ejected by the robot. In addition, for laboratory purposes, an independent hand-made formwork made with a polystyrene base is used, instead of the proposed reconfigurable formwork system. The prototype is physically implemented in 1:1 scale in the laboratory in order to evaluate the process on the basis of construction-scale printing [Fig. 8b].

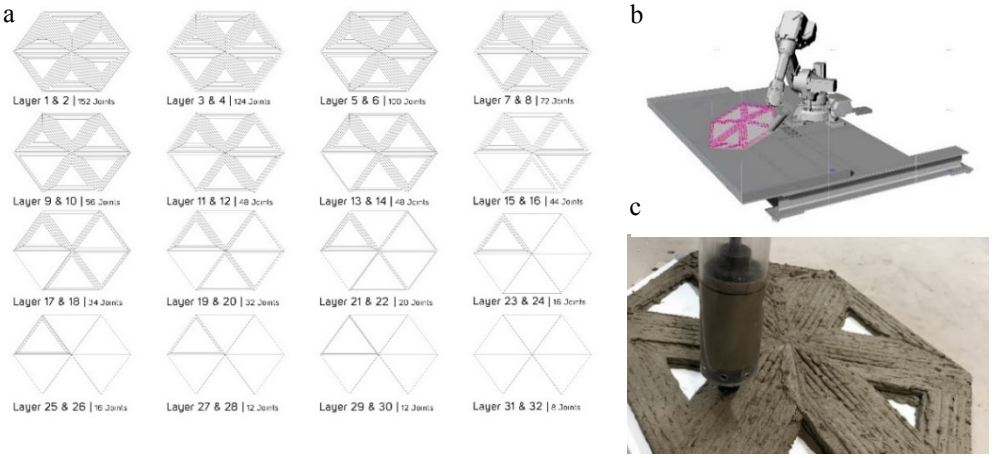

a
Layer 1 & 2 | 152 Joints
Layer 3 & 4 | 124 Joints
Layer 5 & 6 | 100 Joints
Layer 7 & 8 | 72 Joints
Layer 9 & 10 | 56 Joints
Layer 11 & 12 | 48 Joints
Layer 13 & 14 | 48 Joints
Layer 15 & 16 | 44 Joints
Layer 17 & 18 | 34 Joints
Layer 19 & 20 | 32 Joints
Layer 21 & 22 | 20 Joints
Layer 23 & 24 | 16 Joints
Layer 25 & 26 | 16 Joints
Layer 27 & 28 | 12 Joints
Layer 29 & 30 | 12 Joints
Layer 31 & 32 | 8 Joints
b
c

Fig.8 a. Layers of 3DP sample programmed in TACO ABB plug-in, b. 3DP process simulation using TACO ABB plug-in, c. 3DP extruder used in the experimental case study

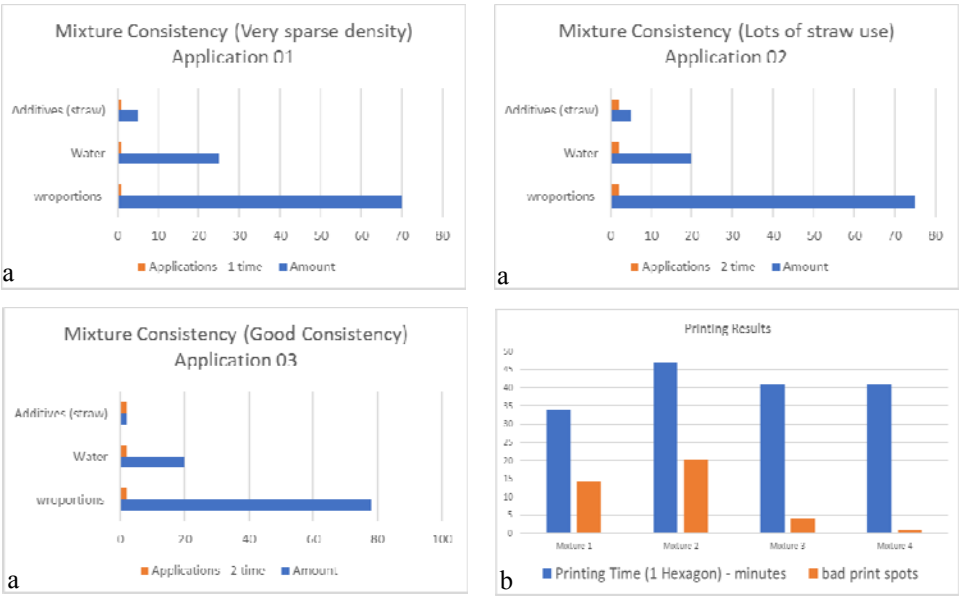


Fig. 9 a. Different consistencies of mixtures, b. 3DP results of the experimental case study

The current experimental 3DP process utilizes an oven-free organic clay-based material with additives. For the purpose of this study, three different mixtures and five different applications have been conducted as it is shown in charts [Fig. 9a]. Using very sparse consistency in the mixture, the printing time of the process can be reduced, but at the same time an increase of bad printing spots (printing discontinuities that affect quality of 3DP) are observed. Also, the use of a large quantity of defective materials creates stronger construction results but increases dramatically the printing time and the bad printing spots [Fig. 9b]. The best mixture used during the experimental study was the one with 78% raw material, 20% water and 2% additives (defective material and Clay/fibers).

6. Conclusion

Despite the rare use of 3DP in the construction industry, the value of applying the proposed integrated methodology can be significant for further research and possible experimentation in architectural and construction examples. Given that the use of 3DP has been limited to elements such as walls, slabs and prefabricated components, future applications might include the manufacturing of complex prefabricated components and free-form shells or even overall structures on-site, assuming the use of suitable robotic mechanism with appropriate manufacturing capabilities like multi-axis 3DP abilities. In order to achieve this, further research is required for the effective application of 3DP techniques in free-from shell structures development, providing an alternative approach for their development in construction scale.

Acknowledgments

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